FIRE EFFECTS AND DELAYED MORTALITY OF MATURE PONDEROSA PINE[1]

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May 2, 2005

Technology Transfer Paper No.
BMPMSC-TTP-05-02

Western forested landscapes have developed under the influence of various natural disturbance regimes. Wildland fire, and forest insects and diseases are some of the more important natural disturbance agents that modify the community of plants in any given forested area over time. All have operated for millennia, but with widely varying ranges of frequencies, intensities, and scope (Agee 1996). Fire and insects usually act abruptly, often violently, sometimes with regularity or periodicity, and generally over a limited time span. Diseases, on the other hand, operate more subtly, in a more or less continuous manner, and typically over a very long time span.

In the dry eastside forests of Oregon and Washington, wildfire has had the greatest influence on the environment in terms of influencing successional patterns of vegetation; and within plant communities influenced by a low-severity fire regime, one often finds a dominance by species that are fire "resisters" (Rowe 1983) (i.e., individuals that can survive low intensity fires without serious injury, such as ponderosa pine, western larch, and Douglas-fir). The low-severity fire regimes are characterized by frequent fires (often <20 years), of low intensity, and with vegetation dominating these ecosystems that are well-adapted to survive such fire events (Agee 1996).

Consequences of Changes in Fire Regime in Dry-Forest Ponderosa Pine Types

Fire exclusion practices since about 1900 have interrupted the frequency of burning in western forest ecosystems. Forest floor fuels have correspondingly increased to levels unprecedented in presettlement times. For example, duff and litter accumulations around large, old-growth ponderosa pines have dramatically increased in depth with each missed fire-return cycle. The lower part of the fermentation layer of duff and the humus layer now comprise a ground fuel that generally burns as *glowing combustion* (Arno 2000). Compositional changes toward shade-tolerant species have also occurred on sites where ponderosa pine is seral, resulting in the buildup of understory ladder fuels that help promote stand-replacing crown fires during wildfires (Arno 2000).

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[1] Paper presented at the Oregon/Washington U.S. Department of Interior, Bureau of Land Management Eastside Forestry Workshop, 17-20 May 2005, Burn, Oregon.

Within the last 2 or 3 decades of fire effects research, a number of studies have revealed that these post-1900 changes may have grave consequences to survival of large-diameter mature ponderosa pines after wildfires and prescribed fires. Ponderosa pine plant communities prior to the 1900s experienced frequent fires as a result of highly combustible leaf litter, an abundance of cured herbaceous vegetation, and a long season of favorable burning weather (Arno 2000). To these factors, we might also add that a limited amount or lack of domestic livestock grazing, the lack of concerted fire suppression efforts, and deliberate ignitions by Native Americans for various cultural purposes, were also contributing factors to a frequent fire influence in many of the stands containing centuries-old ponderosa pine. Duff depth in these stands probably averaged only about half an inch (Keane and others 1990; cited in Arno 2000); and the majority of overstory trees survived each fire, while many of the understory trees were killed (Arno 2000).

In today's dry forest stands that have missed multiple fire events, larger ponderosa pines often have deep accumulations of duff and litter around their bases. Arno (2000) notes that in many of these stands, duff mounds 6 to 24 inches deep have accumulated under old-growth trees, and burning these mounds may girdle and kill the trees.

Over the past decade in northeastern Oregon and southeastern Washington, we have observed increased incidence of delayed tree mortality in the larger size classes of ponderosa pine when the litter and duff accumulations slowly smolder from glowing combustion during prescribed fires, as well as during wildfires, and this fuel is completely consumed to mineral soil (Scott 2002). This mortality ultimately has its origin in dead cambium at the root-crown or subtending roots from injuries sustained in a fire, or from fire-caused rupturing of cells lining resin canals thereby facilitating the flow of resin into root xylem, blocking water conduction through the roots to the crown. Based on our observations, trees with these kinds of injuries to the root structures ultimately undergo moisture stress—usually within just a few years of the injury—and then are attacked and killed by bark beetles and woodborers. Most insect-caused delayed mortality of fire-injured pines seems to occur by year five. Loss of fine roots and basal girdling are common occurrences in complete duff consumption by glowing or smoldering combustion. These trees apparently rely on stored carbohydrates for continuing root function (Harrington 1989; Hungerford and others 1991), but eventually, they undergo several physiological changes after wounding by fire that may seriously affect the tree's water budget (Ryan 2000).

Probability of Cambium Survival In Relation to Depth of Duff Consumed

For large ponderosa pines, a relationship has been observed between depth of duff consumed by fire and subsequent adjacent cambial injury. Ryan (1990) showed that the probability of cambium survival at the root crown declines in mature ponderosa pine as the depth of duff consumed increases. Moreover, logistic regression equations have been developed by Ryan (1990) and Ryan and Frandsen (1991) to describe the probability of cambium survival or cambium mortality, respectively, in mature ponderosa pine, resulting from duff consumption. The graph of the logistic regression equation developed by Ryan (1990) is reproduced in fig. 1 to

illustrate the inverse relationship between mature ponderosa pine cambium survival and depth of duff reduced by prescribed fire. The equation describing this relationship is the following:

Probability of Cambium Survival = 1/(1+e(-2.44+0.13Duff Reduction)) (Ryan 1990)

The depth of duff reduction in the equation above is measured in centimeters. We have recreated the graph with the X-axis displayed in inches to simplify further discussion.

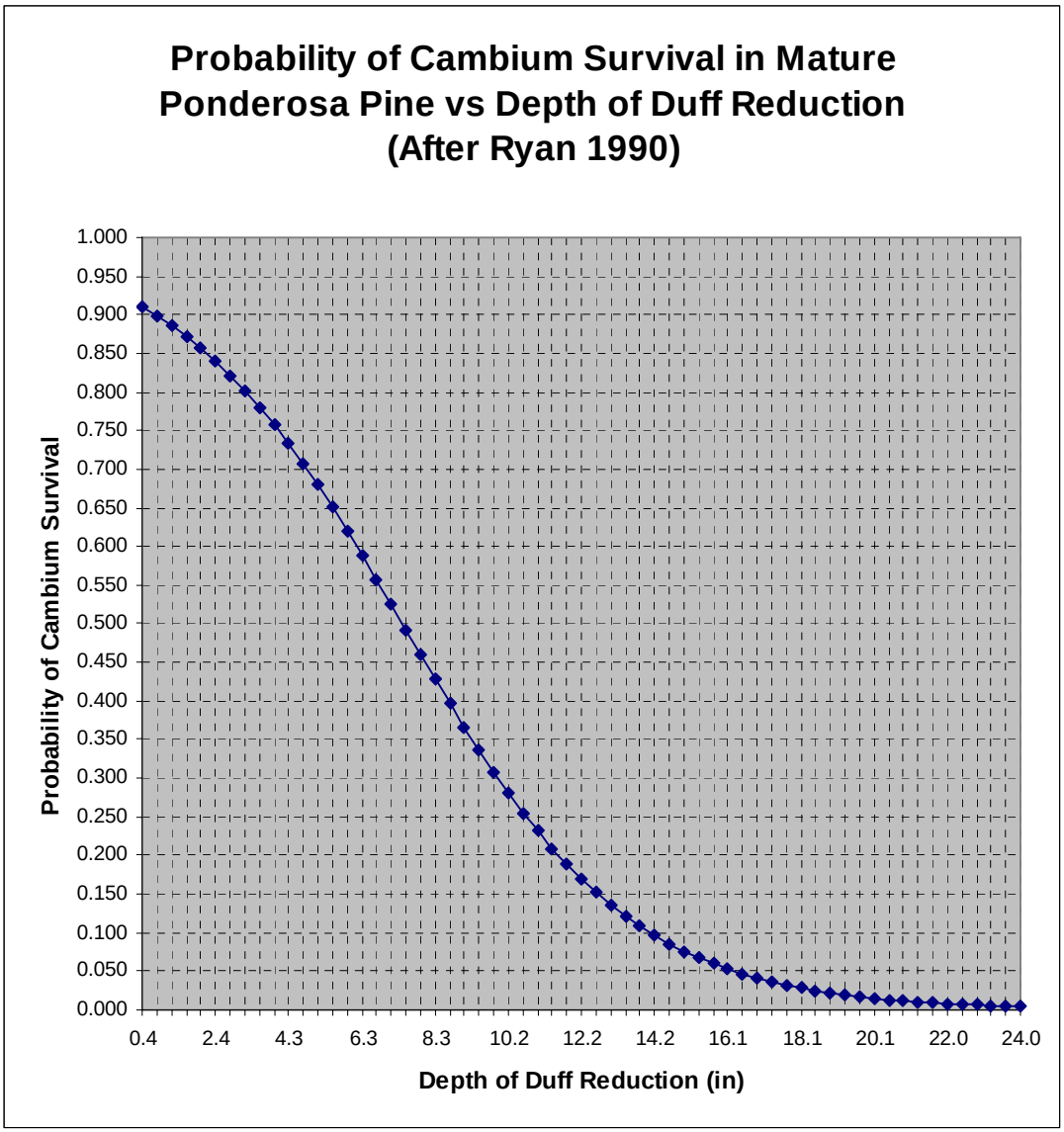

Figure 1. Probability of root-crown cambium survival in mature ponderosa pine based on depth of duff reduction from fire (after Ryan 1990).

It can be seen from this graph that when historic underburning occurred in the dry ponderosa pine types, and depth of duff was generally at most not more than a few inches deep around the

old-growth pines because of the fire-return frequency of the prevailing fire regime in these stands, survival of root crown cambium was high (probably close to 85 or 90 percent). Whereas, when multiple missed fire events have resulted in the accumulation of 8-10 inches of duff and litter, survival after fire of cambium at the root crown declines considerably, to around only 30-45 percent. Consumption of deeper duff levels results in even lower proportions of surviving root-crown cambium.

The consumption of large quantities of heavy forest floor fuel generates large amounts of heat energy at the base of the tree. This energy is often detrimental to root structures. When high duff moisture content is present, some portion of the duff may be consumed, but with only minimal soil heating results (Hungerford and others 1991). When deep, dry duff is completely consumed to mineral soil around large-diameter, mature ponderosa pines by glowing or smoldering combustion, cambium at the root-crown area, and on the large subtending roots, is heated to lethal temperatures. Impacts to soil properties, function, and environment relative to site productivity, may also occur as a result of the heat flux to soils (Hungerford and others 1991). Hungerford and others (1991) report that, except in areas with large fuel concentrations, when dry duff is present, smoldering is the primary source of heat to the lower duff and mineral soil, with temperatures sometimes reaching 500 to 600ºC. A sustained duration of heating occurs during smoldering combustion of duff. This results in lethal temperatures to roots near the soil surface, and to root crown cambium. Lethal temperatures for vascular plants range from 42 to 70ºC and from 24 to 110ºC for nonvascular plants (Hungerford and others 1991). It is commonly believed by most forest scientists that conifer cambium death occurs at 60ºC.

Duff combustion temperatures that remain high for many hours increase the probability of lethal heating of root cambium (Harrington and Sackett 1990; Ryan and Frandsen 1991; Sackett and Haase 1998). In the Fort Valley Experimental Forest fuel reduction burn studies in north-central Arizona in October 1982, temperatures lethal to root cambium were sustained for 72 hours and were found to penetrate 2 inches below the soil surface (Harrington and Sackett 1990). Representing the first burn in 100 years, the Fort Valley fuel reduction burn caused mortality of more than 35 percent of the old-growth ponderosa pines in the forest—trees that had previously survived numerous presettlement fires (Harrington and Sackett 1990). In another study, Ryan and Frandsen (1991) found when fuels accumulated around the base of 200 year-old ponderosa pines were burned in glowing or smoldering combustion, temperatures near the root crown stayed above 300ºC for 2 to 4 hours killing 45% of the cambium samples tested at the root crown of 19 trees.

Mitigating Potentially Lethal Injuries to Large-diameter Ponderosa Pines

Current losses of large-diameter ponderosa pine is an unintended consequence of prescribed fire in the dry-forest ecosystems of eastern Oregon and Washington where fire-adapted tree species developed under a natural fire regime of low-severity, low-intensity, and frequently occurring fire events.

Prolonged lethal temperatures can be avoided around large-diameter pines generally by modifying burn plans and prescriptions to schedule the burn to occur when duff conditions (specifically duff moisture content) would inhibit **complete** combustion of the duff. This is critically important to minimizing lethal injury to roots from prescribed fire. It has been shown

from studies on several different conifer species that duff ceases to burn when it is within the range 100-150 percent moisture content (Frandsen 1987). When moisture content of duff and surface fuels is high, the high latent heat of vaporization of these moist fuels requires a great deal of the energy from combustion to evaporate water, which must occur before the material will ignite and sustain burning (Hawley and Stickel 1948). If there is not enough heat remaining to dry out the duff ahead of the flaming or smoldering front of the fire, and keep the temperature above the kindling point, the fire is extinguished.

This principle can be applied when designing prescription treatments to avoid complete reduction of duff to mineral soil. From a practical standpoint, this may not be as simple as it sounds since few guidelines seem to be available that address this issue for prescription development, and the means of obtaining accurate measurements of duff moisture content in the field are somewhat difficult, tedious, and probably impractical over large areas. Although one could estimate the probability of cambium mortality from complete consumption of a given level of accumulated duff (fig. 1), specific methods to predict the consequences to the tree from given degrees of root injury from fire with much degree of certainty are lacking. Ryan (1990) provided some general guidance in developing prescriptions. In his paper, he stated some likely expectations after fire, if a few "rules" are followed in developing burn prescriptions. We suggest this might be a good place to start. Ryan's "rules" state that:

1. When underburning when duff is wet (ca. 120 percent moisture content), one could expect minimal root injury. [These conditions are much more likely to occur in the spring rather than the fall of the year.]

2. If the duff is deeper than 10 cm and drier than about 35 percent, basal girdling may be a problem for all but the thickest barked trees.

3. In deep-rooted trees expect little additional mortality due to root injury unless duff is also expected to be greater than 10 cm.

4. Expect shallow-rooted species to experience root injury in any prescription that calls for more than 3 cm of duff consumption.

The approach in applying measurements of duff moisture content to avoid complete duff reduction and associated lethal injury to roots during underburns implies a strategy of gradual duff reduction. This is accomplished by reducing forest floor fuels in staged, multiple fire entries, with rest periods of a year or two between entries, rather than reducing duff all at once from a single fire (see Harrington and Sackett 1990). The purpose of a rest period between fire entries is to allow the tree to recover from stress associated with the loss of fine roots that often grow up into the moist duff when duff accumulations are deep. Also, within 3 years of initial burning there is further accumulation of light fire-created fuels made up of fallen needles from scorched canopies; and these fuel accumulations can actually become greater than preburn levels of litter fuels (Harrington and Sackett 1990). Single fuel-reduction burn entries in pine stands with deep duff accumulations can result in a 20 to 50 percent loss of old-growth pine (Arno 2000). Our observations made for several years following various eastern Oregon prescribed burns and portions of wildfires that remained on the ground indicate that resultant mortality levels in these trees may be even higher than reported by Arno (2000).

Thomas and Agee (1986) observed delayed mortality in ponderosa pine and sugar pine in a 4-year study of prescribed fire effects on mixed conifer forest structure at Crater Lake, Oregon. They concluded that careful application of fire would be necessary to preserve the large pine component in the forests of southwest Oregon. Accordingly, they offered suggestions to accomplish the restoration of natural conditions in the mixed conifer stands in southern Oregon that may have applicability for the Blue Mountains as well, including: (1) Fires will need to be low duration to minimize root and root collar heating. Mechanical applications such as scraping some bark and needle accumulations away from the bases of some larger trees may be needed; (2) to assure survival of larger pines, fire prescriptions and monitoring techniques need to be continually refined. The fire needs to be prescribed such that it maximizes the effectiveness of fire-resistant characteristics of the large pines: high resistance to crown scorch because the trees are tall and moderate resistance to cambial heating because of thick bark; (3) Actual duff or soil moisture could be used as a prescription variable, but is awkward to measure; and (4) Monitoring of tree mortality and fuel changes as a result of fire should occur over several years to fully evaluate fire effects. They reported that significant underestimation of tree mortality in their study would have occurred if predictions of fire effects had been based on 1st-year results.

When fires burned in the warm-dry pine communities in ecosystems east of the Cascade Mountains under the historic fire regime, the fire-return frequency facilitated the removal of essentially all the duff and litter from beneath the large-diameter, mature ponderosa pines at intervals ranging from 7-38 years (Agee 1994). Over this period, the depth of litter and duff that accumulated under the mature pines probably amounted to only a few inches, or averaging about half an inch by some accounts (see Keane and others 1990; cited in Arno 2000); and when it ignited it would burn relatively quickly and cause little injury to the cambium or root systems.

Under today's conditions, where many of our dry forests have missed multiple fire return cycles, 6 to 8 inches or more depth of accumulated duff and litter around the base of mature ponderosa pines is not uncommon. However, the rate of loss of large ponderosa pines associated with deep duff accumulations that are completely consumed in either planned or unplanned ignitions is unprecedented today compared with presettlement times. Large old-growth ponderosa pines that have stood on the landscape for multiple centuries, and survived multiple fire events under the historic fire regimes, are now experiencing delayed mortality following the first underburning after many decades of fire exclusion. Hence, avoiding injuring roots and root-crown cambium during prescribed underburns is paramount to the long-term survival of these large old ponderosa pines.

When planning and conducting prescribed burns, application of practices that avoid injuring roots of presettlement ponderosa pines, such as following Ryan's (1990) guidelines, should help preserve the longevity of these trees on the landscape.

Further Research Needs

Some scientists within Forest Service Research Stations are currently investigating ways to preserve these large pines during underburning treatments, or have proposed new studies to evaluate pull-back and other treatments prior to burning that potentially could reduce delayed tree mortality, but funding support to carry out this important research has been largely lacking.

By this document, and other efforts, we endeavor to make more specialists who are involved in fuels reduction treatment programs aware of the unintended consequences of underburning around the large pines when deep accumulations of duff are consumed to mineral soil by glowing or smoldering combustion from a single fire entry. It is our hope that those involved in the fire management program will recognize this need to implement greater mitigation to avoid loss of these large trees in future underburns, and that they would also elevate this issue to higher levels of management within their organizations to encourage support for mitigation strategies. There is clear need to provide adequate funding levels: (1) To support research efforts to develop methods and strategies to improve post-fire results; (2) to implement effective mitigation measures to minimize further loss of the presettlement ponderosa pines; and (3) to implement long-term monitoring of post-fire effects in future fuels treatment projects.

Several mitigation measures are already known to foresters and scientists from the fire effects literature; however, from a fire management perspective, some believe the greatest impediments to addressing the issue of delayed mortality are economic and social rather than ecological.[2] Implementing special mitigation measures and fuel sampling programs to collect detailed data to monitor pre-burn conditions and post-burn results (i.e. for a minimum of 5 years) is time-consuming, expensive, and often not part of our agencies' fire management culture. However, these efforts are needed if the agency is to accomplish resource management objectives within the fuels reduction program and avoid some of the post-fire unintended and undesirable consequences from first- or second-order fire effects, particularly in regard to long-term survival of presettlement ponderosa pines.

Acknowledgements

I would like to thank Dr. Chris Niwa, Pacific Northwest Research Station, Dr. Greg Filip, Forest Health Protection, Pacific Northwest Region, Craig Schmitt, Blue Mountains Pest Management Service Center, Wallowa-Whitman National Forest, and Louisa Evers, Bureau of Land Management, Department of Interior, for their helpful reviews of earlier drafts of this document.

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[2] Letter dated 28 July 2005 from Louisa Evers, State/Regional Fire Ecologist, OSO Branch of Fire and Aviation Management, Bureau of Land Management, U.S. Department of Interior, Portland Oregon.

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